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Real 3D Geometry and Motion Data as a Basis for Virtual Design and Testing

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Abstract
A consistent and accurate digital data model takes a major role during the whole product life cycle of production facilities. This article introduces both technologies: 3D laser scanning for acquisition of 3D geometry date and motion capturing for real motion data with focus on the application in the product life cycle of production facilities. It gives an overview and comparison of different hard- and software solutions. Workflows for concrete tasks in the planning process show how both technologies can be combined and how the acquired data needs to be handled for the integration with CAD tools or Virtual Reality systems. Finally this article gives an outlook on the possible future development of these technologies.

Keywords:
Virtual Reality, 3D Laser Scanning, Motion Capture, Ergonomics

1 MOTIVATION

What is required to successfully distribute and establish products in the domestic and international markets? What does the buyer expect of the product?

Typical expectations are high functionality, quality, reliability, advanced design, efficiency and safety at low cost. In view of this development, the importance of integrating advanced digital technologies into all stages of product development from the first draft to the finished prototype is increasing. A great number of basic decisions in the development process such as variants, layout planning, or FME analyses are made today based on digital three-dimensional data. Combining this basic data with technologies of virtual and augmented reality allows early statements regarding component arrangements, solution variants and space conditions and even on the design of the man-machine interfaces.

In principle, two original types of digital data inventories can be considered. When developing new machines and plants using current CAD systems, 3D CAD data is available at early stages of product development for virtual test environments and for checking on manifold issues. In addition to new designs, optimizations, reconstructions or extensions of existing machines, plants and production facilities have a high priority in planning processes. Under these conditions, early and optimum answers to planning questions frequently require a combination of data on real objects, environments, and real human motion. Advanced processes such as 3D laser scanning for the digitalization of real environments as well as Motion Capture for the recording and analysis of human motions create the conditions for building these complex virtual test environments.

3D laser scanners can be found in many varied areas of industry and research and constitute indispensable tools. Functions such as highly precise measuring, checking and documenting support engineers in their daily work. The use of Motion Capturing in an industrial environment is just starting. But it does create conditions that facilitate realistic motion in human models to achieve optimum results regarding the ergonomic design of machines and plants.

Development processes can be comprehensively accompanied, supported and corroborated by combining this data in a VR environment as the basis for virtual testing and optimization processes, including tests involving humans. Many varied disciplines can utilize this integrated environment and expand it to become a joint basis for work and discussion. It reduces design times, cuts costs and makes decision-making processes transparent [1].

2 INVENTORY-TAKING WITH 3D LASER SCANNING

2.1 Technologies at a glance

Laser scanning, also referred to as laser sensing, “denotes the row by row or grid-like scanning of surfaces or bodies with a laser beam” [13], to obtain a model. Laser scanners only capture surfaces that are visible in the vector of the laser pulse. Rear surfaces or hidden objects remain clouded. This problem is solved today by either dynamic referencing using INS/DGPS (coupling inertial sensors and differential global positioning systems) and additional sensors during measurement or later partially automated referencing. The technologies in Figure 1 offer different options. While airborne laser scanning (ALS) only allows a macroscopic strip-like scan (2D profile lines) of the Earth's surface with typical clouding due to vegetation and other objects, a terrestrial laser scanner (TLS) with spherical scanning (3D scan) in the near range[1] may be able to eliminate clouding by a change of location. Mobile laser scanning (MLS) for the near range combines 2D profile scanners with a movable object on the ground (such as a vehicle) and can be compared to ALS. The most intelligent and most accurate method to date to avoid clouding for relatively small working spaces and short contactless measuring distances is provided by the laser arm that can be manually brought into position in the respective space. Captured data is immediately displayed during measurement as a 3D point cloud and serves as the basis for a quasi control circuit. The configuration of various devices also depends on the size of the object to be scanned and the associated measuring accuracy.(see Figure 1).

Regardless of their technological design, laser scanners generate a finite number of points over the time of a measurement that are digitally stored with a position and brightness value. A model representation in point form is limited to this information and does not contain any topology as compared to that of a surface or volume model. It is not always necessary to generate surfaces (see Figure 4). Point clouds depict a quasi-surface in a specific quality depending on point density, point thickness and color value. Interpretation by software tools is critical in this case.

2.2 Prerequisites for obtaining an effective model

Laser scanning is of interest for capturing existing machines and plants or general objects for which there are incomplete digital models or no models at all. Elementary variables are the achievable accuracy or resolution with the associated systematic distance variation, capturing rate or which volumes per time unit can be captured and used. Plants can be dimensioned from a few to several hundred square meters. The TLS is currently best suited for such object sizes at a measuring accuracy in the millimeter range and flexible positioning (see Figure 1). The main criteria that applies is the visibility of the components that are relevant for documentation and revision. If complete three-dimensional objects are to be captured, the number of measuring points always is >1. This brings up the problem of location referencing of each individual scan. Practicable methods include referencing using pass markers, feature extraction, and iterative closest point (ICP) methods.

2.3 Laser scanning field tests

Technology	Accuracy	Resolution	Range	Rate	Model size
ALS	+/-15cm at 1200m axially +/-0,6cm at 1200m horizontally	3 to 50cm	1200 to 3500m	up to 100,000 P/s	∞
MLS	+/-1cm at 100m	0.0025° angular 0.004° scan line	2 to 300m	up to 11,000 P/s	∞
TLS	+/- 2 to 3mm at 25m	0.009° angular 0.00076° scan line	1 to 80m (phase difference)	up to 120,000 P/s	∞
Laser Tracker	+/- 50 µm at 10m	0,5 µm length measurment	up to 35m	up to 10,000 P/s	70x70m
Laser Scan Arm	+/-35 to 50 µm	-	up to 95mm	up to 19,200 P/s	4x4m
Laser Microscope	+/-1 to 10 nm	up to 450 nm in axial direction up to 150 nm in lateral direction	up to 16.5mm	-	20x20mm

Figure 1 : Laser capturing systems (Sources : Hansa Luftbild, FARO, Riegl, Zeiss, Optech)

Field tests with the FARO LS 880 laser scanner in a typical production environment have shown that the lowest possible resolution is selected for a maximum capturing rate and that color information is deactivated, if required (see Figure 2).

Resolution	Time per Scan	Photo Option	Re-Positioning
0.09° (1/10)	1 min	~ 7 min	~ 5 min
0.045° (1/5)	5 min	~ 7 min	~ 5 min

Figure 2: Capturing time examples with FARO LS 880

Smaller resolutions also produce considerably less data volumes (see Figure 3). Models can be represented smoothly and without reduction as segmented VRML by 3D viewers in VR environments.

Resolution	Data Volume FARO Scene	Data Volume xyz
0.09° (1/10)	~ 5/150 Mbytes	~ 50 Mbytes
0.045° (1/5)	~ 18/165 Mbytes	~ 200 Mbytes

Figure 3: Data volume color scan examples with FARO

Pass marker referencing is only useful for individual plants or smaller production areas since the resolution for geometry fitting (reference) is insufficient at a distance of >7m[2] and the effort of dragging the pass markers along would rise tremendously for big objects (such as halls). Suitable algorithms that can handle feature extraction and ICP (such as Geomagic) can achieve overlap accuracies of a few millimeters between two scans. The strong divergence of two laser pulses that leads to a decrease in point resolution as distances increase should be taken into account. Accuracy may have to be adjusted depending on the respective application. A TLS scan at a low resolution is sufficient for simple visual VR reference in conjunction with motion capturing test scenarios. But if components such as those of a machine tool are to be included in a CAD re-engineering process, systems such as a laser tracker or the laser scan arm may be better suited since they permit considerably higher accuracies of approx. 35-50 µm. A TLS is in this context suitable for simple surface feedback requiring accuracies of several mm only, such as in a VR visualization. A detail size of several centimeters can only just be resolved visually and geometrically in a scan.

In testing practice with TLS, a square site grid with a maximum width of 5 to 6m and a resolution of 0,09° has

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[1] approx. 1 to 10 m away from laser source

[2] Empirical determination using the FARO Scene software

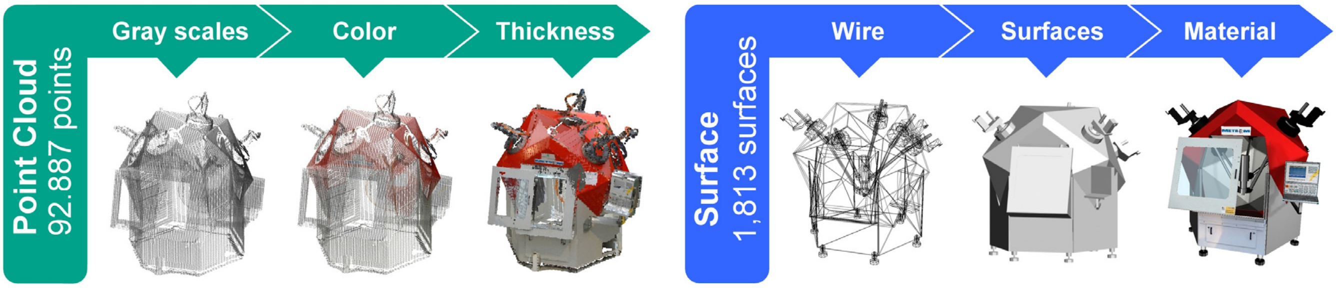

Figure 4 : Model representation – point cloud, area model

proven its worth[3] if no pass markers are to be used. The relatively small grid width automatically eliminates clouding at a high object density. An overall model is achieved by iterative coupling of stationary measurements. It should be noted that error propagation may lead to curvatures[4] of planar areas (such as a building footprint) that can result in deviations in the meter range over 100m of object length. This problem can be solved using a higher-order system of coordinates to which the orientation and positioning of scans are aligned as well. If objects take an area of up to 100 sq. m and referencing accuracy[5] requirements of a few centrimetres, this factor can typically be neglected.

2.4 Direct utilization of point cloud records: a hands-on example

TLS is preferable for generating static and highly accurate models for documentation and visual referencing[6]. TLS allows capturing machines and plants and their associated structures in a relatively[7] short time and using them as reference. MLS is unsuitable for typical production environments due to its specific application requirements, although the technology of automatic locating holds enormous potential for TLS in the future [3][11][12]. TLS can clearly do better than practice-oriented accuracies for manual digitalizations up to +/- 100mm.

The visTABLE planning system is an example of directly using point cloud data in VR. The basis for planning, including detail planning is created using a reference of the structure as a point cloud. The point cloud model primarily acts as visual collision control in this context or defines the static spatial limitations in a production facility, similar to a surface or volume model. It is likewise possible to segment individual parts of the point cloud and thus extract machines and plants as a model and arrange them accordingly in the planning model. This method, is also called "rapid planning" [2] ,allows planners to obtain high-quality statements in shorter time.

Point clouds can also be used as references for surface feedback in design tools such as AutoCAD or ProEngineer. Manual generation of surface models based on a point cloud is still relatively complex today and may take up 75% of the time for inventory-taking, which equals four times the effort [4]. It can be derived from this that it is useful to mix existing CAD data with scan data to reduce planning costs. The Pointools software renders mixed records in conjunction with visualization tools such as 3D Studio Max and avoids complex surface reconstructions, for example when visualizing motion capture records in an existing production area. 3D laser scanning allows the generation of basic data for virtual studies of the most varied issues in the process of developing machines and plants.

3 INTEGRATION OF THE HUMAN ELEMENT INTO THE PLANNING PROCESS

3.1 More ergonomic man-machine interfaces

A well thought-out ergonomic construction of a machine together with an ergonomic design solution represent a major factor determining the decision in favor of or against a product. Buyers expect that a machine handles well, does not cause fatigue and provides ease and safety of operation, maintenance, retooling and service. Humans themselves are the yardstick of ergonomics. The design of the interfaces between man and machine has the purpose of allowing clear and unambiguous operation, operator safety and optimization of work flows.

The European Machine Directive 98/37/EC(MRL) [5] [14] (updated as from 12/29/2009 by 2006/42/EC) requires machine manufacturers to minimize physical and mental strain on machine operators by applying ergonomic principles as early as in the blueprint stage of machines and plants. To comply with this criteria means for a designer the early inclusion of ergonomic considerations in the process of development at a time when all that is available is CAD design data and the relevant provisions in the respective standards. Experience gained from decades, analyses of customer requests and well-designed components from suppliers may help improve ergonomics but the relevant provisions in European standards [6][7] must be observed. One approach to meeting these requirements is to use the CAD data for first ergonomic studies. Data obtained by 3D laser scanning can be integrated into virtual test environments in the form of point clouds or models from surface feedback to optimize the remodeling or extension of existing environments such as assembly stations.

3.2 Virtual ergonomics tests

The construction of virtual test scenarios focusing on the ergonomic design of man-machine interfaces has decisive advantages in product design over the use of desktop systems alone. A bond is created between humans and geometry by the true-to-scale representation and interaction with the test scene so that geometry is perceived by the human and can be evaluated using a structured approach. In addition to perception by a real person and his or her natural flow of motion, the integration of virtual human models into the test environment provides an opportunity to assess issues under specific anthropometric aspects.

The functionality of digital human models used in VR environments is already quite comprehensive while they are constantly being adjusted to their real entities. Digital VR-capable human models such as JACK[8], RAMSIS

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[3] Averaged across all scanner sites

[4] So-called "banana referencing"

[5] Absolutely across all scans

[6] Quasi 3D photograph

[7] For manual inventory-taking

[8] Digital human model for improvment the ergonomics of product designs by Tecnomatix

VR[9], VirtualANTHROPOS[8][9], and IDO:ERGONOMICS[10] provide the user with comprehensive model variants from anthropometric databases and catalogue. Depending on the analysis task, the model can be defined with characteristics such as age, gender, percentile[11], region of origin and special physical features. The models are supported and moved by approx. 90 joints with up to five axes which allow biomechanically correct movements [8][9]. Visualizing the visual, gripping and working spaces using auxiliary geometries and graphic representation of important joints in the VR environment enables designers to make fast statements regarding the comfort or discomfort of defined model types in relation to the geometries to be examined (see Figure 5).

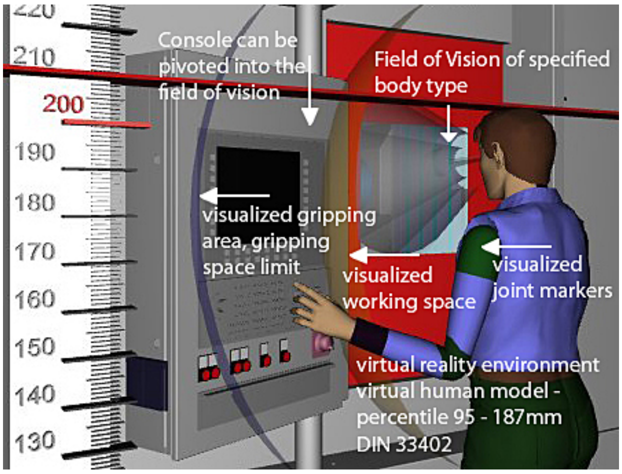

Fig. 5: Checking the view of tool/workpiece with a digital human model

3.3 Creating virtual test scenarios: hands-on examples

In cooperation with machine toolmaker StarragHeckert GmbH[12], a virtual check was performed during the development of the 5-axis HEC 630 X5 processing center to assess the view of the tool-workpiece interface and to check accessibility of the working space and of specific modules if they require disassembling and assembling as part of service operations [10].

The objective of this virtual pre-examination was to eliminate ergonomic deficiencies regarding views and accessibility at an early point in the planning process of the HEC 630 X5 and subsequent designs.

The IDO:ERGONOMICS VR environment was used to combine all data relevant for the viewing process (see Figure 6).

- the CAD design data of the HEC 630 X5,
- the ergonomic issues relating to the design,
- the standards and directives on ergonomic machine design, and
- the human factor (real person and digital model) as a yardstick of ergonomics.

The CAD data generated in the design process was exported to VRML format, a standard exchange format for 3D scenes and at the same time one of the target formats of the VR environment (in addition to Performer Binary and Open Inventor).

The checklist and evaluation sheets of BGI 5048-1, "Ergonomic Machine Design", and the associated BGI 5048-2, "Information on the Ergonomic Machine Design Checklist" were selected as working material from the statutory and European directives and standards. This practical guideline includes the most important criteria of ergonomic machine design from 30 individual standards and directives.

In a third step, the relevant issues were assigned to the 11 higher-order inspection topics of the checklist. Relevant subordinate questions for examining the VR environment were derived from the more general topics "Machine Access", "Workplace Dimensioning", "Observation of the Working Cycle in the Manufacturing Process", "Manually Operated Controls" and "Keyboards, Keys, and Input/Output Devices".

The examined scene was completed by using the user himself and the virtual human model of the IDO:ERGONOMICS VR environment. Depending on the specification selected, the virtual model visualizes the viewing space of the person, the gripping and working space (depending on physical body dimensions) as well as discomfort markers on joints indicating extreme postures (green: normal, yellow: critical, red: discomfort) using auxiliary geometries

The first examination was performed subjectively using the users body dimensions and movements in the VR environment. No deficiencies regarding access and viewing space were detected. The subsequent use of the virtual human model allowed the inclusion of different physical dimensions and proportions in the viewing process.

These functionalities of digital human models make it possible to determine ergonomic constraints for different physical dimensions, e.g. that people in the 5-percentile will not be able to reach the outer function button unless the control panel can be pivoted, for example, in parallel to the machine frame. Direct movement and turning the body towards the control panel would be required, which is an unfavorable sequence of movements for the user from an ergonomic point of view. The objective studies using different body proportions allow an optimized design of the man-machine interface.

The special advantage of virtual scenarios is the combination of all relevant data and information in one environment, the VR system. Ergonomic questions such as view and accessibility can be assessed easily when taking a systematic approach. The geometry can be evaluated based on the researcher's own feeling while the use of the virtual model of a human being allows the implementation of more functionality for evaluations taking into consideration anthropometrics. Measuring functions integrated into the VR system and the movement of components further support fast results. Early and, most of all, true-to-life assessment of design data in conjunction with man as the standard for ergonomics is ensured.

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[9] Computer-supported anthropometric mathematical system for vehicle occupant simulations by Human Solutions

[10] Digital human model for analysis of ergonomics by IC:IDO

[11] In ergonomics: the distribution characteristics for the dimensional proportions of the human body, stated as a percent

[12] International manufacturer of high precision milling machines

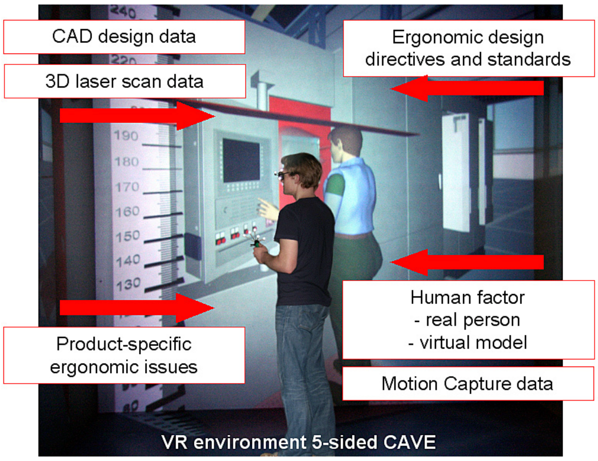

Figure 6: Virtual test scenario, focus on ergonomics, combination of all relevant data in the VR environment

4 INTEGRATION OF REAL SEQUENCES MOVEMENTS INTO VIRTUAL TEST SCENARIOS

4.1 Capturing motion (e.g. at an assembly station) using Motion Capture

In addition to inclusion early-on of ergonomic issues into the design process of machines and plants, the evaluation and optimization of physically existing environments are important factors for improving the productivity and safety of human operators. The combination of various technologies in the planning and optimization process offers great benefits. If the goal is restructuring or expansion of manual assembly stations, planning should be performed both with real people and using virtual corroboration. Creating virtual test scenarios allows the merger of existing geometries that may have been captured using 3D laser scanning and resources and facilities that are being developed and are only available in the form of CAD data. Motion Capture allows inclusion humans and to transfer a human's natural sequence of movements to a virtual environment.

Motion Capture can be used to record human movements and to store them in data formats that allow analysis of the recorded movements and their use on more advanced studies such as virtual avatars. Stored functional content such as the display of critical joint angles by discomfort markers in the virtual human model allow detection of uncomfortable sequences of movement and their elimination by an advanced virtual optimization process.

4.2 Motion capture systems for whole body tracking

Whole body movement tracking as required for studies of complex sequences of movement is mainly applied through optical, electromagnetic, electromechanical, and inertial systems. Optical systems require multiple special cameras with a fast refresh rate and high resolution. The actor's body is equipped with active (light-emitting diodes) or passive markers (reflecting, non-luminescent markers) that are captured by the camera [VICON][13]. Despite their high accuracy and the actor's freedom of movement, optical systems are not suitable for capturing movements at assembly stations. This would take an enormous camera mounting effort. When using passive markers, other reflections in the room have to be prevented since they would be captured as ghost markers.

Electromechanical systems consist of linkages (exo-skeleton) equipped with potentiometers that measure the rotation and orientation of the actor's joints [such as Gypsy 6™][14]. The disadvantage of such systems is limitation of movement due to the design constraints of the skeleton. Their use in ergonomic studies is not beneficial since natural movements cannot be performed without limitations.

In electromagnetic systems, a transmitter unit generates a low-frequency electromagnetic field. The sensors attached to the actor are activated by induction, the data is transmitted to a control unit that determines position and orientation in the 3D space. The disadvantage of these systems for motion capturing at assembly stations is the rather small radius of action that is limited to the magnetic field generated, susceptibility to interference and the actor's cabling.

Motion capture systems with acceleration/inertial sensors like the "MOVEN" whole-body motion capture suit by Xsens currently offer the most comfortable options for motion capture at assembly stations. It is based on miniature sensors that are integrated in a suit and do not require external markers and cameras. Data transfer is wireless and in real time. No calibration effort is required, and the actor's movements are not restricted, enabling a large scope of action and recording of any type of movement (see Figure 7).

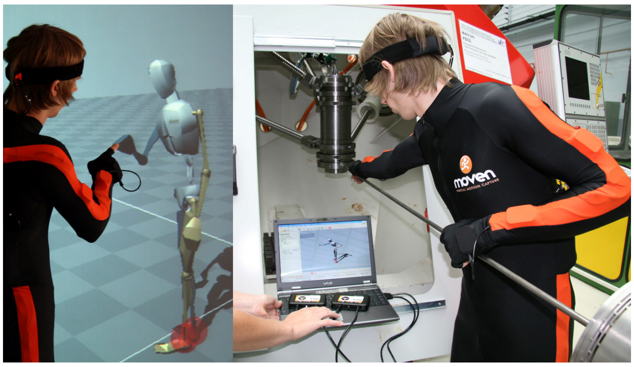

Figure 7: Motion capture at a real machine tool and virtual interpretation by the real actor.

The 16 inertial sensors integrated into the suit record 3D position, 3D orientation and, optionally, acceleration, speed, angular speed and angular acceleration of each segment. The data obtained is entered for the avatar of the VR application. Skeleton models provide the link between the two processes. The skeleton model of the actor who performs the movements and the skeleton of the virtual human model to which the motion data is applied. The skeleton structure has to be identical, which includes topology and the number and labeling of skeleton elements. The MOVEN SDK[15] provides data stream motion data for immediate use in the virtual scene. The standardized BVH data format (BioVision Hierarchical data) provides an interface for data transfer into systems with integrated virtual human models.

The movements are exported based on global translation and the rotations of the joints.

5 ABSTRACT AND OUTLOOK

For optimum support of design processes across design stages, the methods of modern 3D digitalization have to increasingly be integrated and coupled with planning and development tools. Complex questions and early product assessments require simple but interdisciplinary solutions.

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[13] Provider of infrared cameras for motion capturing

[14] System of the company Meta Motion

[15] The „Moven“ Software Development Kit

Further development of 3D laser scanning can enhance the creation of virtual test scenarios, particularly in the fields of optimization and extension of existing environments. Scanned inventory data and CAD design data can be integrated as early as in the blueprint stage for early detailed planning, e.g. when changing the design of existing plants. Another objective is to obtain automatic surface feedback based on feature recognition algorithms that allow fast creation of basic 3D data for real-time VR environments. Automatic networks are used in precise 3D body scanning to use 1:1 human models for analyzing optimum sizing. With increasing accuracy of TLS and improved derivatives thereof, surface feedback of production areas will become more accurate and cost-effective. Another requirement is fully automated referencing of TLS data across multiple measurements. This is to ensure that highly precise point cloud records are determined in their position and orientation towards each other as accurately as possible.

Motion Capture is for the most part applied in the professional entertainment industry to develop video games and create special effects. Another established field of application is sports medicine. Human movements are recorded and used to optimize the athletes' performance. However, inclusion of the human operator in the development of technological systems is increasingly required by the market so that motion capturing applications are finding their way into industrial planning. The design of interfaces that are more suitable for humans is the top priority for using this technology.

Optimum support for ergonomic issues in the planning and development of machines and plants will require the further merger of ergonomically functional, VR-capable human models and motion data from motion capture systems. The functionality of the human model can be used for fast and unique capture of motion occurring in real time, e.g. discomfort indication in critical joint positions such as assembly operations with a limited gripping space. The examination of the virtual environment also creates an opportunity to place resources in the planning process in such a way that critical postures and sequences of movement are corrected and optimum working conditions are created for different physical proportions (example: 5-, 50-, 95-percentile study; DIN 33204). The more human features are included in the planning process through modeling, the better suited interfaces can be designed for humans.

Which digital data will be used in VR scenarios will always depend on the issues to be studied in the respective planning process and on the desired results. The intelligent and controlled application of advanced technologies such as 3D laser scanning and motion capture in combination with virtual reality technologies facilitates the creation of comprehensive testing environments for early planning and design evaluations. This may prevent later time-consuming and costly design changes from the start.

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